Executive summary

Prospects for head- and crosswind dependent aircraft separations in the context of wake vortex safety and airport capacity

Application to Schiphol airport

An exploratory investigation is made on the possible mitigation of wake vortex separation standards of head- and crosswind operations during landing and take-off phase. A simplified analysis shows that landing capacity losses during head-wind conditions can be fully recovered by employing time-based instead of normal ICAO separation standards. The analysis also indicates that even shorter separation distances (and therefore higher landing capacity than in zero head-wind conditions) might be considered, because in head-wind conditions the vortices of the preceding aircraft tend to be further below the glide-path.

It is also shown that for steep descent approaches (favourable for noise abatement) the potential capacity gain in headwind landing conditions can be even larger. These findings, when applied to the wind statistics of Schiphol Airport, suggest that a significant increase in mean airport capacity is possible. Tactical application could be very effective to prevent delays during headwind conditions.

Also, a significant fraction of time, airport operations at Schiphol Airport occur in cross-wind conditions during which vortices are effectively blown out of the flight corridors. Based on cross-wind statistics, a significant increase in airport capacity is feasible (both during landing and take-off).

Report no.
NLR-TP-2005-398

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Classification report
Ongerubriceerd

Date
June 2006

Knowledge area(s)
Aëro-akoestisch en experimenteel aërodynamisch onderzoek
Veiligheid (safety & security)
ATM & Airport operaties

Descriptor(s)
wake vortex
airport capacity
safety

This report is based on the paper submitted to the 25th ICAS Conference, Hamburg, September 2006

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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Customer	National Aerospace Laboratory NLR
Contract number	
Owner	National Aerospace Laboratory NLR
Division	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified

Approved by:

Author	Reviewer	Managing department
16-6		16/6

Summary

Many airports in Europe and the US are operating close to their maximum capacity and the growth of air traffic causes increasing delays, especially during peak hours. In Europe aircraft usually operate under Instrument Flight Rules (IFR). For approach and landing minimum aircraft wake vortex separations depend on aircraft weight category (small, large, heavy), largely in agreement with ICAO recommendations. For departures, usually time based separations apply.

The current wake vortex separation rules are generally believed to be sufficiently safe, but rather conservative in certain weather conditions.

The present report addresses the possibility of applying head- and/or crosswind depending reduced aircraft separations during the landing and departure phase. Taking the mean annual wind conditions for aircraft operations at Schiphol Airport as an example, an initial estimate is made of the potential landing and departure capacity benefits for different wind-dependent aircraft separation strategies.

For steep approach procedures (as being considered for reduced noise emissions) the initial assessments indicate a large potential gain in airport capacity. However, further study will be needed to assess the practical limitations and safety aspects for the proposed modified aircraft separation strategies.

Contents

(23 pages in total)

List of symbols

b_v	*lateral distance between vortices*
d_{min}	minimum radar separation distance
D, L	aircraft drag and lift force (Fig. 10)
L	parameter defined in equation (3)
P	cumulative probability, equation (2)
PDF	probability density function, equation (1)
T	thrust force, see Fig. 10
t	time
Δt	(minimum) time separation, equation (6)
t_v	vortex age, equation (10)
u_C	crosswind velocity at 10m height
u_H	headwind velocity at 10m height
$\bar{u}_H$	mean headwind, see equation (1)
U	wind speed
U_{10}	wind speed at 10 m height
V	true airspeed of the aircraft
W	aircraft weight
w_v	sink speed of wake vortices
x	distance along ground
X	max runway landing capacity, eq. (12)
Δx	separation distance between aircraft
x_f	position of follower aircraft, eq. (8)
x_v	position of vortices, see equation (9)
z_f	vertical position of follower aircraft
z_v	vertical position of vortices, eq. (9)
$\Delta z_{v,ILS}$	vertical distance to vortices, eq. (11)
Greek symbols	
α	shape factor, used in equation (3)
β	scale factor, used in equation (3)
γ	glide slope angle
ρ	air density
σ_H	standard deviation headwind, eq. (1)
χ	capacity gain in %, eqs. (13) and (14)
Γ	vortex strength, equation (6)
sub-fixes	
$f/g/v$	follower/ generating aircraft/ vortex

1 Introduction

Many of the major airports in Europe and the US are operating close to their maximum capacity and the growth of air traffic causes increasing delays, especially during peak hours. In Europe aircraft usually operate under IFR and runway throughput is then mainly constrained by wake turbulence safety aspects. During approach and landing minimum aircraft separations are based on aircraft weight categories (e.g. ICAO small, large, heavy). Recommended minimum separations are generally significantly larger than minimum radar separation (e.g. 2.5 NM) and for departures time-based separations are being applied (see Fig. 1). Although wake-encounters are reported by pilots occasionally, the current separation rules are generally believed to be sufficiently safe, though rather conservative in certain weather conditions (e.g. strong atmospheric turbulence, strong headwind and/or crosswind conditions).

Runway throughput during peak hours, reduction of flight delays and increased airport capacity are of large economic interest. Therefore, the possibility of employing dynamic (weather dependent) safe separation rules is intensively studied in Europe and the US. In the US these activities are mainly coordinated by NASA and FAA. Following the AVOSS project [1-2], NASA now co-ordinates a project [3-5] in order to safely change ICAO definitions for WV separation standards. In the US, prime emphasis is on Closely Spaced Parallel Runways (CSPR). For single runway operations, NASA follows a step-by-step research/implementation approach, first concentrating on crosswind dependent departures, because these require only a short weather prognostic horizon.

In Europe modified procedures for closely spaced parallel runways have only been considered for Frankfurt airport. A Wake Vortex Warning System [6] has been developed, but has not yet been put into operation. However, the HALS/DTOP dual approach procedure is now in use [7]. Mainly as part of EU co-funded projects, considerable research effort has been made to reduce aircraft

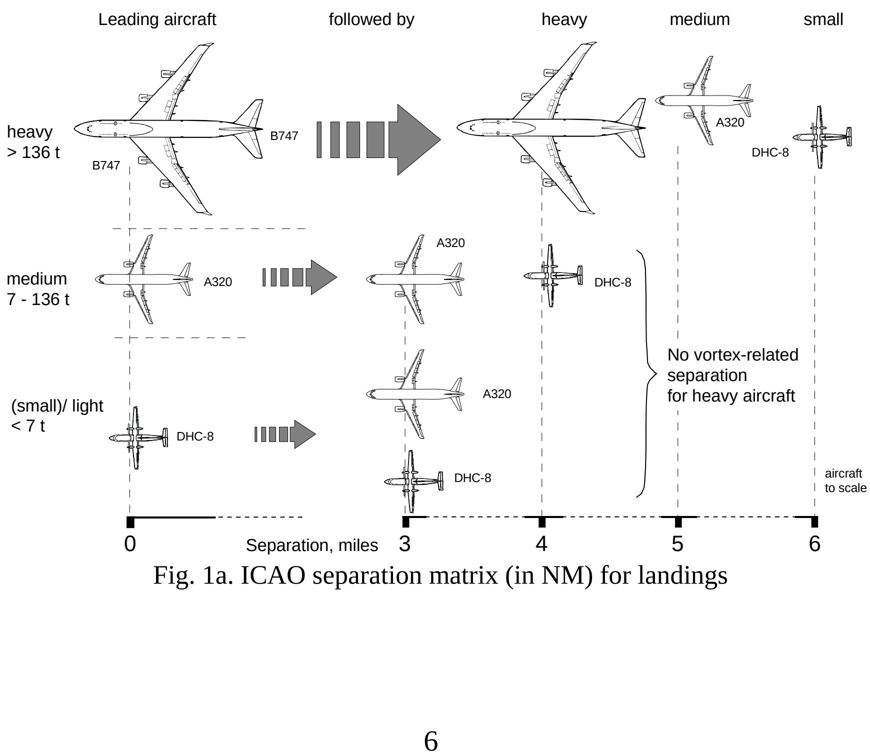


Fig. 1a. ICAO separation matrix (in NM) for landings

<table>
<tr><td colspan="2" rowspan="2">separation time (seconds)</td><td colspan="3">trailing aircraft</td></tr>
<tr><td>H</td><td>L</td><td>S</td></tr>
<tr><td rowspan="3">Leading aircraft</td><td>H</td><td>90</td><td>120</td><td>120</td></tr>
<tr><td>L</td><td>60</td><td>60</td><td>60</td></tr>
<tr><td>S</td><td>45</td><td>45</td><td>45</td></tr>
</table>

Fig. 1b. Separation times (in seconds) for departures

separations for single runways. In the S-Wake [8] and ATC-Wake [9] projects, the influence of weather (wind and atmospheric turbulence) on transport and decay of vortices was investigated. In addition, Eurocontrol is developing a strategy for Time-Based Separations (TBS) in order to maintain airport capacity during headwind conditions [10]. A recent study by Eurocontrol [11] showed the potential benefits of weather dependent separation concepts. Eurocontrol also manages the EU research project CREDOS, which focuses on reduced separations for departures.

At Schiphol winds are relatively strong and due to the runway architecture and noise abatement procedures there is a tendency for aircraft operations in relatively strong crosswind. Therefore, Schiphol Airport must be considered as a promising candidate airport for applying dynamic, wind dependent separation rules. Based on mean wind statistics, the present report considers the potential capacity benefit of some aircraft separation concepts. It is also shown that during head-wind conditions steep descent approaches (e.g. up to 5.5 deg glide path angle, as e.g. applied at London City Airport), could provide significant additional capacity combined with a reduced noise impact.

The prevailing wind conditions for aircraft operations at Schiphol airport and potential benefits during cross-wind situations are discussed in section 2. Specific headwind dependent separation procedures during approach are discussed in section 3. Conclusions and recommendations are given in section 4.

2 Wind conditions at Schiphol airport

Long time period averaged wind statistics for Schiphol Airport are available from [12-13]. The cumulative probability distribution of total wind speed (at 10m height) is shown in Fig. 2. It is to be noted that the wind speed during the 1971-2000 period is on average lower than in the 1951-1975 period. This is most probably due to the building activities at and near the airport, leading to a higher surface roughness and less wind near the ground. Actual wind speed and direction probability densities (per 10^4 samples) are shown in Fig. 3. Very strong winds only occur for a small fraction of time and then predominantly from SWW or, to a somewhat smaller extend, from NEE. Low wind speeds have the tendency to occur more homogeneous from all directions than high wind speeds.

Because runway usage also depends on wind magnitude and direction, these wind statistic data can not directly be used to assess the occurrence of tail-, head- and crosswind operations. JAR ACJ AWO-131 [14] presents a realistic model for the simulation of automatic landing systems. It is based on UK aircraft operations at a mix of airports. The cumulative probabilities of total-, head-, tail- and crosswind components (Fig. 4) confirm that aircraft normally operate in head-wind conditions and in limited cross and tailwind.

Actual data for Schiphol Airport have been obtained at NLR by correlating takeoff and landing operations with actual winds (according to ICAO METAR specifications) during a long period of time. The probability density function for head and tailwind operations at Schiphol appears to be well represented by a normal distribution with an average headwind $\bar{u}_H$ of 7.3 knots (3.75 m/s) and a standard deviation σ_H of 6.8 knots (3.5 m/s), so:

$$PDF_{u_H} = \frac{1}{\sigma_H \sqrt{2\pi}} e^{-0.5\left(\frac{u_H - \bar{u}_H}{\sigma_H}\right)^2} \tag{1}$$

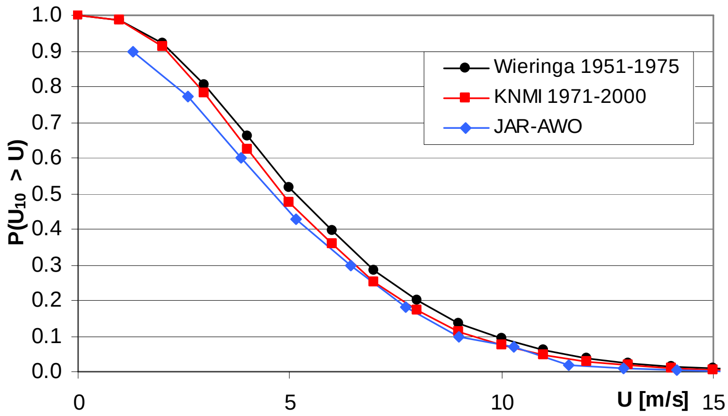


Fig. 2. Cumulative probability for exceeding a certain total wind speed at Schiphol [12-13], compared to JAR ACJ AWO-131 [14].

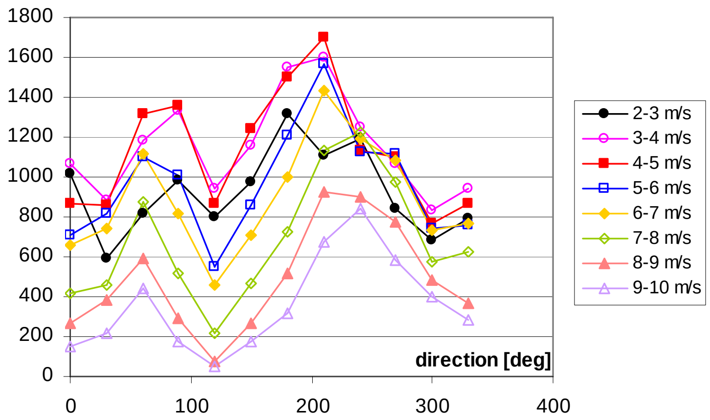


Fig. 3. Probability density for total wind speed and direction at Schiphol Airport (per 10^5 samples, [11]).

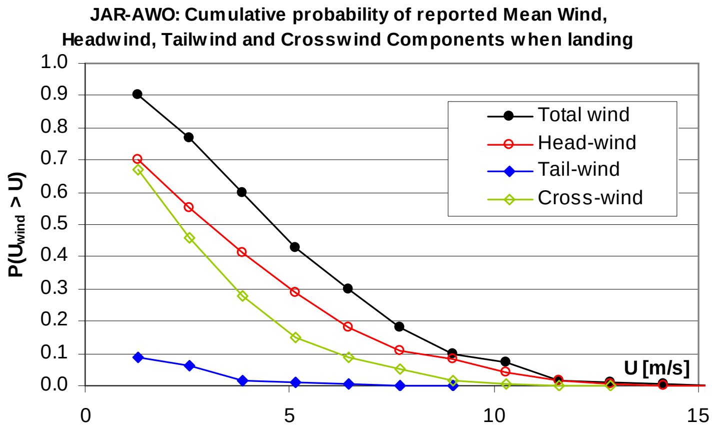
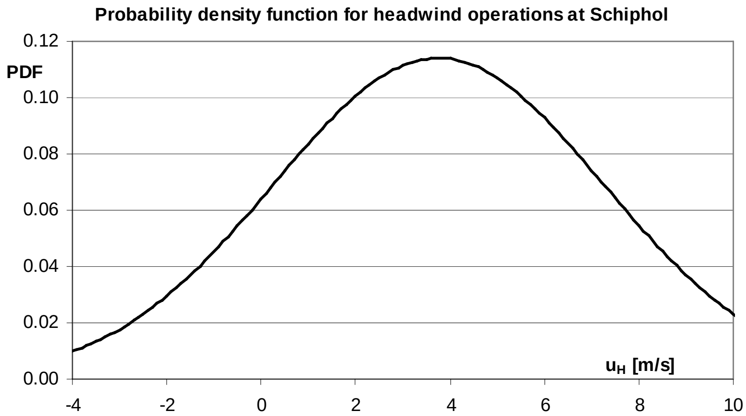


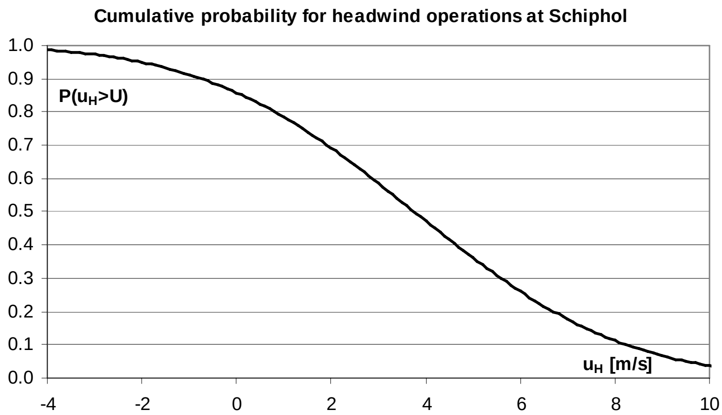
Fig. 4. Cumulative probability of total-, head-, tail- and crosswind components for a set of UK aircraft landings (according to JAR ACJ AWO-131 [14].

$$P(u_H > U) = 1 - \int_{-\infty}^{U} PDF_{u_H} du_H \qquad (2)$$

These headwind functions, shown in Fig. 5, confirm the preference for headwind operations.



a) Probability density distribution for head and tailwind operations



b) Cumulative probability for aircraft operations exceeding a certain headwind

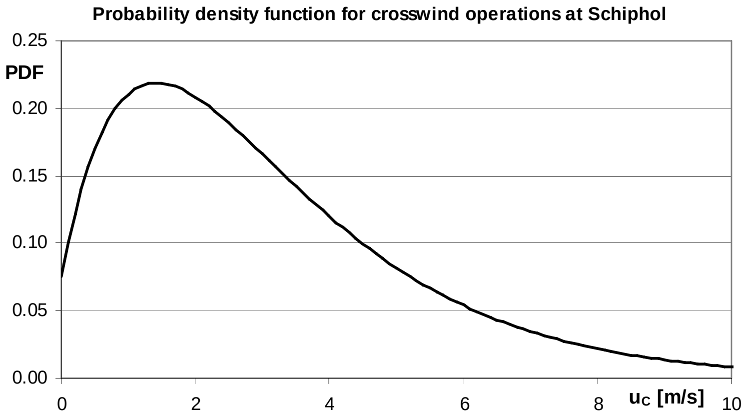
Fig. 5. Mean head and tailwind operation conditions at Schiphol airport (NLR data)

Crosswinds from the left and right are about equally alike at Schiphol and the probability density for crosswind operations at Schiphol is well approximated by a gamma distribution ($PDF_{u_C} = 0$ for $u_C \le L$):

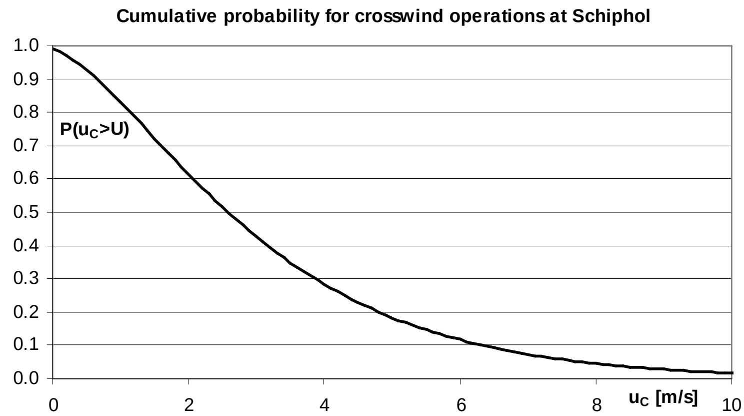
$$PDF_{u_C} = \frac{1}{\Gamma(\alpha)\beta}\left(\frac{u_C - L}{\beta}\right)^{\alpha-1} e^{-(u_C-L)/\beta} \tag{3}$$

$$P(u_C > U) = 1 - \int_0^U PDF_{u_C} du_C \tag{4}$$

With L = -0.2313 m/s, shape factor α= 1.97, scale factor β = 1.70134 m/s, $\Gamma(\alpha)$ = 0.98768. Results shown in Fig. 6 indicate that for a significant portion of time substantial crosswinds occur: e.g. u_C> 3 m/s for about 43% of the time.



a) Probability density distribution, cross- wind operations



b) Cumulative probability for aircraft operations exceeding a certain crosswind

Fig. 6. Mean crosswind operation conditions at Schiphol airport (data from NLR)

In the earth atmospheric boundary layer the total wind speed will in general increase with altitude. On average this can be described (see Fig. 7) with a logarithmic profile:

$$U(z) = U_{10} \frac{\log(z/0.03)}{\log(10/0.03)} \tag{5}$$

U_{10} is the total wind speed at 10m height. For Schiphol a surface roughness height of 0.03m applies [13]. If crosswind is above a certain limit at the reference height of 10m, this is not yet necessarily the case along the entire ILS glide path, because wind direction can change with height. In neutral and unstable atmospheric conditions these variations are relatively small. They only become substantial in stable atmospheric conditions [12].

The relatively strong crosswind conditions at Schiphol Airport, were also noted in an airport climatology study by Meteo France and Met Office [15-18] as part of the S-Wake project [8]. In that study crosswinds larger than 3.11 m/s (6 knots) were assumed sufficient for blowing the vortices out of the glide slope. Results are shown in Fig. 8.

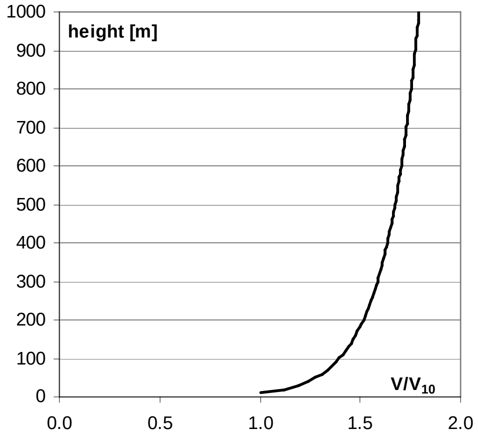


Fig. 7. Average wind increase with height

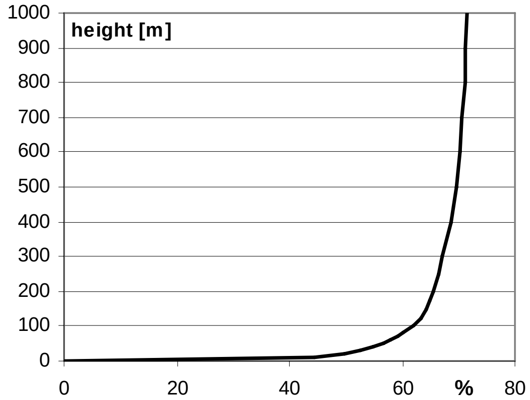


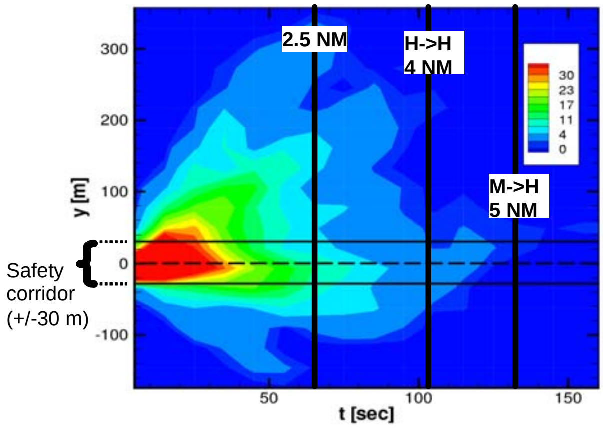
Fig. 8. Probability to exceed crosswind of 6 knts (Schiphol airport, from S-Wake [17]).

In agreement with Fig. 7, the probability to exceed the crosswind limit increases with eight. At 10m height the probability to exceed 3.11 m/s (6 knts) is about 40%, in reasonable agreement with the data shown in Fig. 6. Atmospheric turbulence and stability, which have an effect on wake vortex decay, were also considered (see [18] for details). Table 1 shows how often the entire glide slope (between 0 and 2 km) would be in a favorable wake vortex decay or crosswind condition. Again, with respect to these aspects, Schiphol airport compares favorable to other European airports.

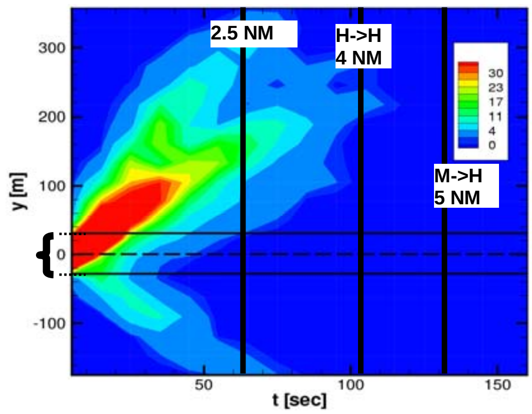
The favorable effect that crosswind has on lateral wake vortex transport is also nicely demonstrated in the analysis made by DLR (as part of the S-Wake project [8] for LIDAR wake measurements made at Memphis airport. With the LIDAR placed close to the runway threshold Fig. 9 shows the probability density function for the lateral position of the vortices with respect to the ILS flight corridor, as function of the vortex age. Fig. 9a shows the results for all wind conditions (554 cases in total). Fig. 9b shows results for crosswinds above 2 m/s (252 cases). ICAO separation standards (5 NM for Medium behind Heavy and 4 NM for Heavy behind Heavy) have been approximately indicated. Clearly in crosswind conditions much reduced aircraft separations (e.g. 2.5 NM radar separations) are possible.

Site	**% time**
Schiphol	49
London Heathrow	47
Charles de Gaulle	41
Memphis	39
Toulouse	33
Frankfurt	24

Table 1: Mean percentage of time for which the entire glide slope is in a favourable crosswind or wake decay condition (result from S-Wake [18]).



a) all winds: 554 cases



b) u_c > 2 m/s: 252 cases

Fig. 9. 2-D frequency distributions (in ‰), for lateral position of wake DLR analysis of Memphis data, S-Wake [8]).

3 Benefits for modified aircraft separations during head-wind approaches

3.1 Mathematical framework

Current wake vortex separation rules prescribe fixed minimum separation distances between aircraft in landing phase, depending on the aircraft weight class (see Fig. 1). On final approach the aircraft fly with a constant (aircraft type dependent) airspeed. In strong head-wind conditions the flying time, needed to travel the minimum separation distance, increases. This leads to a substantial loss of runway capacity.

To maintain runway capacity, Eurocontrol has proposed to use weight-class dependent time-based, instead of distance-based, separations. Fig. 10 gives a sketch of the aircraft and wake trajectories in a local earth-fixed co-ordinate system and defines the main parameters

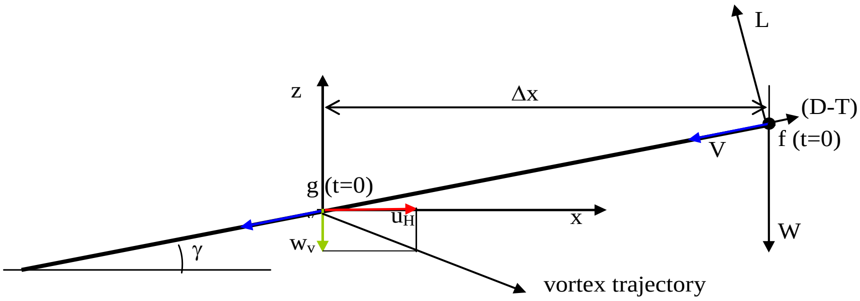


Fig. 10. Sketch of aircraft positions and vortex transport along ILS approach glide path at *t*=0, in an earth fixed co-ordinate system (*x*, *z*).

The origin of the (*x*, *z*) co-ordinate system denotes the position of the wake generating aircraft (*g*) at time *t*=0. Both aircraft are assumed to fly with the same constant true airspeed *V* and exactly along the ILS glide path. At *t* = 0 the following aircraft (*f*) is at $x = \Delta x$. The following aircraft needs a flying time Δt to arrive at the *x*= 0 position. The flight path angle γ (normally 3 degree) is retained as free parameter since, because of noise abatement procedures, some airports operate with a much larger glide path angle (e.g. London City Airport with γ= 5.5 deg.). The noise benefits of such steep approaches have been investigated in the EU co-funded projects Sourdine and Sourdine II [22].

The wake vortices sink with a velocity w_v, due to mutual induction of the counter rotating port and starboard vortices. The sink speed is given by (see e.g. [19]):

$$w_v = \frac{\Gamma}{2\pi b_v} = \frac{C_L V b^2}{4\pi AR b_v^2} = \frac{W}{2\pi\rho V b_v^2} \tag{6}$$

Γ is the vortex circulations strength, b_v is the lateral vortex spacing (usually about 0.7*b*, where *b* is the wingspan), C_L is the lift coefficient, *AR* is the wing aspect ratio, *W* is the aircraft weight (balanced by lift *L*, drag *D* and thrust *T*) and ρ is the air density. Evaluating equation (6) it appears that the vortex sink speed during final approach phase is between 1.5 to 2 m/s for a large range of transport aircraft. In the derivations that follow the vortex sink speed w_v and headwind u_H are assumed constant. Suffix *v* relates to the vortices of the preceding aircraft. Fig. 11 shows a phase diagram of aircraft and wale vortex positions.

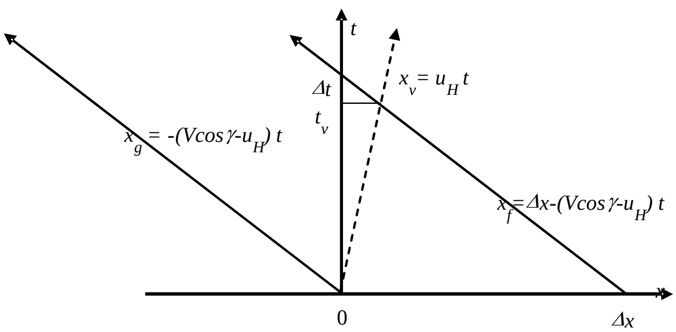


Fig. 11. Phase diagram for wake vortex transport and aircraft positions in

headwind conditions, for aircraft at constant true airspeed V on final approach.

The separation time Δt between the aircraft depends on the flying speed, wind conditions and the separation distance Δx:

$$\Delta t = \frac{\Delta x}{(V\cos\gamma - u_H)} \tag{7}$$

The position of the following aircraft as function of time is given as:

$$\begin{aligned} x_f &= \Delta x - (V\cos\gamma - u_H)\, t \\ z_f &= x_f \tan\gamma \end{aligned} \tag{8}$$

The position of the wake vortex pair, generated by the preceding aircraft, is:

$$\begin{aligned} x_v &= u_H t \\ z_v &= -w_v t \end{aligned} \tag{9}$$

Condition $x_v = x_f$ is of specific interest, because it defines the vertical distance and the wake vortex age t_v of the vortices from the preceding aircraft that are below the following aircraft. From equations (8, 9) it follows as:

$$x_v = x_f \Rightarrow t_v = \frac{\Delta x}{V\cos\gamma} = \left[1 - \frac{u_H}{V\cos\gamma}\right]\Delta t \tag{10}$$

The vertical distance of the vortices below the glide path $\Delta z_{v,ILS}$ follows from:

$$\Delta z_{v,ILS} = (w_v + u_H \tan\gamma)\, t_v \tag{11}$$

With minimum time separation between aircraft equal to Δt sec and a minimum horizontal (i.e. radar) separation d_{min}, the maximum runway landing capacity X (landings per hour) is:

$$X = \frac{3600}{\max\{\Delta t, (\cos\gamma . d_{\min}/V)\}} \tag{12}$$

In the next section this is evaluated for different aircraft separation strategies. Unless otherwise stated, γ = 3 deg, w_v= 1.5 m/s, V_g = V_f = 70 m/s and d_{min}= 2.5 NM are assumed. As reference condition the zero headwind case with Δx=5 NM (medium behind heavy) is taken, leading to: Δt= 132.5 sec and $\Delta z_{v,ILS}$= 198.7m.

3.2 Application to different aircraft separation strategies

3.1.1 Constant Δx and true airspeed V, but increasing Δt

According to current ICAO rules, a minimum separation distance Δx between aircraft is required, independent of head wind. With a constant true airspeed V the corresponding separation time Δt increases with headwind according to equation (7) and runway landing capacity χ (in % compared to the no-wind case) decreases:

$$\chi = \left[\frac{\Delta t_{u_H=0}}{\Delta t_{u_H}} - 1 \right] * 100\% = -\frac{u_H * 100\%}{V \cos\gamma} \tag{13}$$

According to equation (10), with fixed Δx and true airspeed V, the wake vortex age t_v remains ***independent of head-wind***, but the vertical distance to the vortices increases according to equation (11).

Basically there are two possibilities to compensate for the loss of airport capacity: flying with a constant groundspeed (requiring an increased true airspeed) while keeping Δx at minimum ICAO distance, or flying with the same true airspeed V, but reducing the aircraft separation distance Δx below minimum ICAO spacing. In order to remain on the required ILS track, both options require suitable thrust and lift management, but this is not discussed here.

3.1.2 Constant Δt and Δx, with increased true airspeed V.

In this case the ICAO minimum aircraft separation rule (Δx= 5NM) remains satisfied and the separation time between aircraft (Δt= 132.5 sec) remains equal to the no-wind reference case. The true airspeed V^* needs to be increased: $V^* = V + u_H / \cos\gamma$. Then, according to equation (10), the vortex age t_v will become smaller (so the vortex is less decayed). For aircraft flying in trail with the same speed, the wake induced rolling moment is not depending on their airspeed [19]. However, roll control capability increases proportional to the square of the flying speed. Therefore, increasing the flying speed will reduce the severity of a wake encounter. Also the sink speed of the vortices w_v becomes smaller, because of the reduced vortex circulation strength (equation (6)). The distance to the vortices $\Delta z_{v,ILS}$ is however still weakly increasing with headwind (Fig. 12a).

Therefore increasing the airspeed, as to keep groundspeed, can restore the capacity losses related to headwind, apparently without significant drawbacks for wake encounter severity (the only drawback is possibly a somewhat less decayed vortex, but this will at least partly be compensated by the increased roll control capability). The ground speed at touchdown is equal to that for the no-wind case. However, the higher airspeed requires extra thrust, which will have a detrimental effect on noise emission.

3.1.3 Constant Δt and airspeed V, with reduced separation distance Δx

Assume that true airspeed V and separation time Δt are maintained as in the no-wind reference case. Then, according to equation (7), the separation distance Δx needs to become less than the minimum ICAO limit. The wake vortex age t_v reduces according to equation (11). However, the vertical distance of the vortices below the glide path ($\Delta z_{v,ILS}$) remains larger than in the no-wind case.

3.1.4 Constant airspeed V and reduced Δt, with $\Delta z_{v,ILS}$ equal to the no-wind case

If we assume that the vertical separation distance to the vortices offers the main safety margin during final approach (but see the remarks at the end of section 3.3) one could require that this distance is kept equal to the no-wind case (e.g. equal to $\Delta z_{v,ILS}$= 198.7m, when assuming a reference wake vortex sink speed of $w_{v,REF}$=1.5 m/s for the

Δx= 5NM case). In headwind conditions this allows a reduction in time and distance separation between aircraft, albeit the wake vortex age t_v will diminish. The corresponding runway capacity gain χ (in % compared to the no-wind case) depends on the glide slope angle γ and w_v and follows from manipulations with equations (11) and (12). Keeping wake vortex sink speed as a free parameter, but requiring $\Delta z_{v,ILS}$= 198.7m ($w_{v,REF}$=1.5 m/s) gives:

$$\begin{aligned}\chi &= \left[\frac{\Delta t_{u_H=0}}{\Delta t_{u_H}} - 1\right] * 100\% = \\ &= \left\{\begin{aligned} &\frac{u_H}{w_{v,REF}}\left[\tan\gamma - \frac{w_v}{V\cos\gamma} - \frac{u_H \tan\gamma}{V\cos\gamma}\right] \\ &+ \left[\frac{w_v}{w_{v,REF}} - 1\right]\end{aligned}\right\} * 100\%\end{aligned} \tag{14}$$

The last term between brackets immediately indicates a potential capacity gain (irrespective of headwind) for aircraft producing vortices with a high sink velocity, e.g. for aircraft having a relatively large inboard loaded wing [19], leading to a small vortex spacing b_v (see equation (6)). If vortex sink velocity is large then, for a certain $\Delta z_{v,ILS}$, the time separation between aircraft can be reduced and runway capacity will increase. The first term between brackets shows the positive effect of headwind. The potential gain due to headwind decreases if the sink speed w_v of the vortices increases. For given vortex sink speed the potential capacity gain in headwind increases with glide slope angle.

3.2 Discussion of results

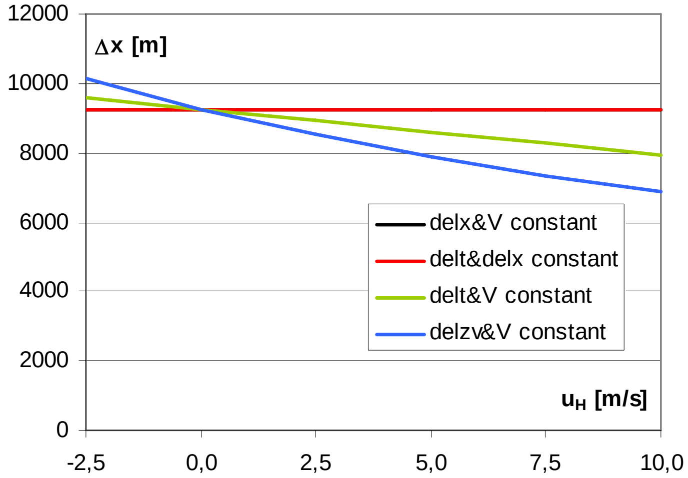
For a reference case Δx= 5 NM, the influence of headwind for the different aircraft separation strategies has been computed and is shown in Figs. 12a-d. For constant Δx strategy, the separation time between aircraft (Fig. 12b) and the height above the vortices (Fig. 12d) increase with headwind. The vortex age remains equal to the no-wind case (Fig. 12c).

The capacity loss can be compensated by increasing the true airspeed (such as to maintain groundspeed) while maintaining aircraft separation distance. This leads to a smaller vortex age t_v (Fig. 12c), but the height above the vortices (Fig. 12d) still remains somewhat larger than in the no-wind case.

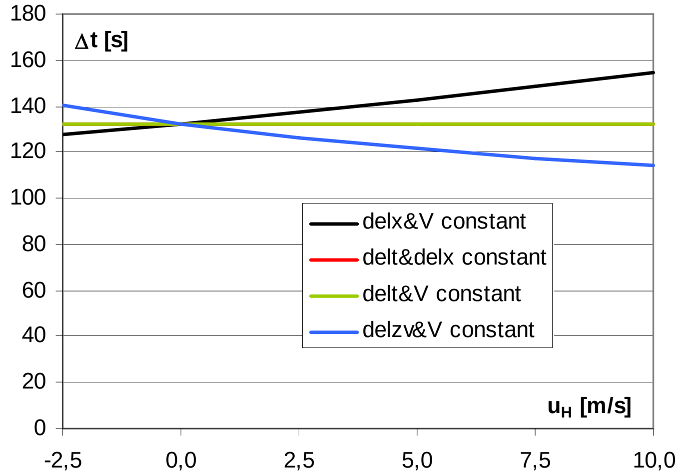
The capacity loss can also be compensated by decreasing the separation distance while maintaining the airspeed. Again this leads to a smaller vortex age t_v (Fig. 12c), but the height above the vortices (Fig. 12d) remains larger.

Requiring that the vertical distance to the vortices remains at least equal to the no-wind reference situation (assuming w_v= 1.5 m/s), results in a headwind dependent reduced separation time (Fig. 12b), but the age of the vortices below the glide path is now further reduced (see Fig. 12c).

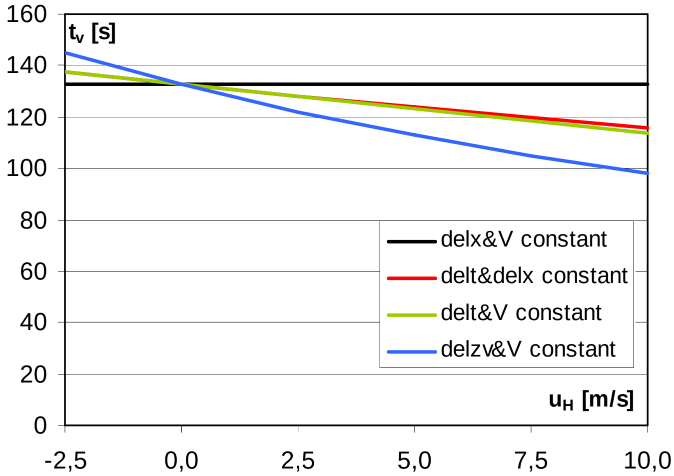
The decrease of runway landing capacity under current ICAO rules has been computed with equation (13). In headwind conditions Δt strategies (either with increased airspeed or with reduced separation distance) can lead to a full recovery of runway capacity loss. However, the Δz_v strategy potentially offers considerably increased runway capacity, especially when combined with steep approaches. The computed momentary capacity gains are shown in Fig. 13, depending on headwind magnitude.



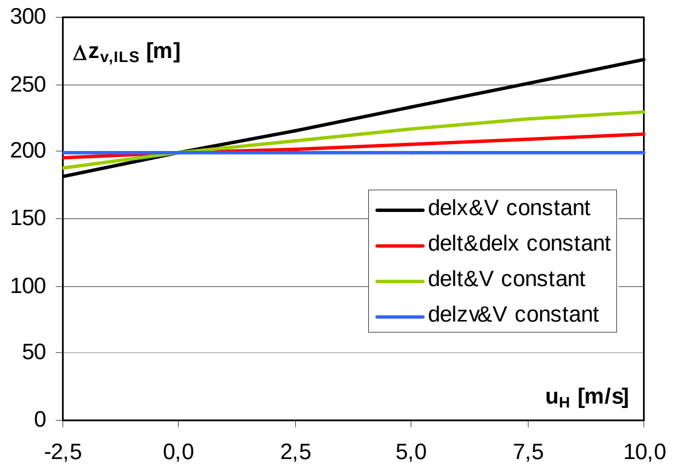
a) Δx



b) Δt



c) t_v



d) $\Delta z_{v,ILS}$

Fig. 12. Variation of Δx, Δt, t_v and $\Delta z_{v,ILS}$ as function of headwind u_H for aircraft separation strategies with Δx, Δt or Δz_v independent of headwind. Reference case with 5 NM separation and γ= 3 deg, V= 70m/s and w_v= 1.5 m/s. The red line represents a case with modified air-speed in order to maintain Δt for given Δx.

To assess the total accumulated effect on total mean airport capacity $\overline{\chi}$, the probability for headwind operations at Schiphol airport was taken into account with:

$$\overline{\chi} = \int_{-\infty}^{+\infty} \chi(u_H).PDF(u_H)du_H \qquad (15)$$

An analysis was made for two assumed vortex sink velocities (w_v= 1.5 and 2.0 m/s, corresponding to a $\Delta z_{v,ILS}$ requirement of either 198.7 or 264.9 m) and the results in Table 2 show less capacity gain when minimum $\Delta z_{v,ILS}$ requirement is increased.

It should be noted that the computations were made for the Δx= 5 NM case (medium behind heavy), but as long as the separation distances stay below minimum radar separation distance d_{min} the predicted capacity changes equally apply to other aircraft pairs.

However, a final note on the validity of the main assumption (during final approach wake-vortex safety is largely due to vertical vortex separation distance) is at place. From the Frankfurt FLIP study [23], vertical deviations from the ILS glide path are expected to be less than +/- 40 m (2σ probability). For aircraft at relatively large separation distance (e.g. Δx= 5 NM) the vertical sink distance is at least 198.7 m (for a relatively low vortex sink speed w_v=1.5 m/s), so well below the flight corridor. Therefore the vertical distance to the vortices seems indeed a main factor contributing to the wake vortex safety. However, if separation distance becomes less (e.g. 3 or 2.5 NM for equally sized aircraft) the vertical distance to the vortices will decrease correspondingly and wake vortex decay and navigation accuracy will become more an issue for the overall safety. The same observation applies for the safety condition close to the ground, were vortices are prohibited to sink because of ground proximity.

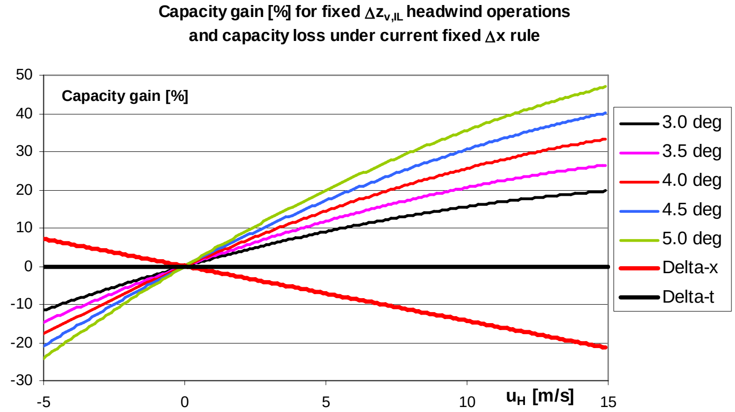


Fig 13. The change of runway landing capacity with head wind velocity, from equation (14). Constant Δx, Δt or Δz_v aircraft separation strategy (Δz_v strategy for different glide slope angles) with V= 70m/s, w_v= 1.5 m/s and γ= 3 deg.

separation strategy	γ [deg]	$\overline{\chi}$ [%], $w_v = 1.5$ [m/s]	$\overline{\chi}$ [%], $w_v = 2.0$ [m/s]
Δx	3.0	-5.36	-5.36
Δt (Δx < or V>)	3.0	0.00	0.00
Δz_v	3.0	6.42	3.47
Δz_v	3.5	8.38	4.95
Δz_v	4.0	10.35	6.42
Δz_v	4.5	12.31	7.89
Δz_v	5.0	14.28	9.37

Table 2: Effect on (annual mean) landing capacity of Schiphol airport, for various aircraft separation strategies.

4 Conclusions and recommendations

Applying ICAO separation rules for landings during headwind conditions leads to unnecessary loss in airport landing capacity.

These losses can simply be regained by applying equivalent time-based, instead of distance-based, separations.

It was noted that a time based approach where separation distance is maintained, but ground speed is increased, will improve the roll controllability. However, it needs to be investigated if increased airspeed on final approach is acceptable (e.g. slightly larger thrust and thus noise).

Analysis shows that in headwind conditions, even with time-based separations, the vortices are further below the glide path than in zero wind conditions.

Further reduced aircraft separations seem therefore feasible, leading to an increased landing capacity.

Much larger benefits might be obtained if reduced separations are combined with steep approaches.

Vortices are also blown out of the flight corridor during sufficiently strong crosswind conditions, a minimum crosswind requirement of 3.11 m/s (along the whole glide path) has been suggested [18].

During strong crosswind conditions this offers the possibility to safely reduce aircraft separations, both for approaches and landings.

Time based and other strategies lead to a lower vortex age, but it should be noted that in stronger winds the ambient turbulence will generally increase (according to conventional atmospheric turbulence models turbulent kinetic energy is proportional to the wind speed), which leads to a more rapid decay of wake vortices. So a decreased vortex age does in this case not necessarily mean a stronger vortex.

In section 2 it was noted that, on average, relatively strong head- and crosswind conditions occur during aircraft operations at Schiphol airport. This is favorable for introducing wind dependent aircraft operations to either maintain or increase airport capacity.

At Schiphol, headwind landing operations with u_H> 5 m/s occur for almost 40% of the time and under these circumstances, with ICAO separation rules formally applied, this leads to a runway landing capacity loss of at least 7.2% (but much larger during stronger headwind conditions). This landing capacity loss can be **regained** by applying time-based, instead of distance based rules. However, if distance above the vortices is maintained as in the no-wind case, at u_H= 5 m/s a 5.0% (w_v=2 m/s) to 9.1% (w_v= 1.5 m/s) **increase** of runway landing capacity seems possible. Even much larger capacity gains seem possible with steep approaches.

It was shown that **on average,** under current ICAO separation rules, Schiphol suffers a landing capacity loss of about 5.4% because of headwinds. This can be avoided with time-based separation rules. Theoretically with headwind dependent time separations, such as to maintain constant vertical distance to the vortices, mean landing capacity gains between 6.4 and 3.5% are possible (see table 2) and even (much) larger gains for steep approaches.

It should be noted that combining steep approaches (noise abatement) with reduced aircraft separation times allows increased airport capacity without much increased noise impact. This option should therefore be further investigated.

Also at Schiphol the minimum crosswind for blowing the vortices out of the approach corridor (3.11 m/s (6 knots), as suggested by the S-Wake study) is exceeded for about 40% of the time. So for a considerable part of the time the aircraft separations might be reduced up to minimum radar separation (subject to runway occupancy time restrictions). This also offers significant increases in airport landing capacity.

Crosswinds also blow the vortices out of the take-off flight corridor, giving prospects for reduced time separations during departures. Especially, since in this case only a relatively short wind prognostic time horizon is needed.

It should be noted that the present study investigated the potential use of wind dependent aircraft operations for increased capacity or reduced delays, using rather idealized but realistic conditions. In practice there will be additional constraints (e.g. persistency and predictability of the winds, manageability by the Air Traffic Controllers) which will decrease the achievable benefits. These should be further investigated.

The following items need further investigation:

- Weather persistency aspect (e.g. by analysing METAR data of Schiphol airport).
- Weather monitoring and prediction (to identify safe weather prognostic horizon).
- Optimum aircraft sequencing and departure routes (e.g. such that heavier aircraft stay downwind from medium and small aircraft).
- Optimum ILS glide slope intercept procedures to avoid small aircraft to intercept with ILS from below.
- Safety aspects of the wind dependent procedures (compliance with ESARR4).
- Investigate to what extend the separation rules are now actually followed in order to assess the real benefits of the proposed procedures.
- Perform probabilistic safety assessments (e.g. with NLR WAVIR [20-21] method) in order to take account of the probabilistic nature of the atmosphere and the variability in aircraft operations.
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Acknowledgements

Reference was made to the work performed by Met-Office and DLR during the 5th Framework EU project S-Wake. The author also wants to thank his colleague G. van Es who provided the operational wind statistic data for Schiphol Airport. The knowledge for the present study has been largely assembled during the author's participation in EU co-funded research projects WAVENC, S-Wake and ATC-Wake.

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